Seismic damage to churches: Observations from the 2011 Lorca (Spain) earthquake

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SUMMARY:
On 11 May 2011, an earthquake of magnitude Mw = 5.1 hit the city of Lorca, Spain. The earthquake caused a large amount of damage over a number of buildings. The paper presents an overview of the damages observed during a two-day reconnaissance trip made two weeks after the earthquake. After reviewing the regional tectonic settings and seismicity, the paper addresses the performance of masonry churches during the earthquake. The damage patterns are analysed in light of the type of masonry construction that was found. The level of damage is also quantified according to an existing grading procedure for churches based on theoretical failure mechanisms.

Keywords: Lorca earthquake, church damage, masonry, church mechanisms

1. INTRODUCTION

On 11 May 2011, at 18:47 (local time), an earthquake of magnitude Mw = 5.1 hit the city of Lorca in the southeast region of Murcia, Spain. Lorca is a moderate size city whose origins date back to the Bronze Age and that has a current population of about 90000. The city, which sits on both banks of the Guadalentín river and on the hillside of a IXth century castle, has numerous historical buildings, including churches, Roman villas, palaces and other monuments. The earthquake caused extensive damage to both recent and older constructions in Lorca, along with 9 casualties and around 250 injured. Although earthquakes of such magnitude are expected to cause limited damage, it is believed that both the shallow depth of the hypocentre and its close distance to the city are the main reasons for the significant damage that occurred. The depth of the hypocentre was between 1 and 2 km and at a distance of about 2 km from Lorca, according to data from the United States Geological Survey and the European Mediterranean Seismological Centre. Although damage outside Lorca was reported as being minor, the earthquake was felt along the Mediterranean Coast, in Murcia, Alicante, Valencia and Madrid. The main earthquake was preceded by another event of magnitude Mw = 4.5, at 17:05 (local time). Although this foreshock was relatively weak, damage to some structures was also reported.
Two weeks after the earthquake, normality appeared to have returned to Lorca. However, a closer look indicated that a significant amount of damage occurred over a large number of buildings. In this context, the proposed paper presents an overview of the damage observed in churches during a two-day reconnaissance mission that took place two weeks after the earthquake and involved researchers from the Portuguese Faculty of Engineering of the University of Porto and the University of Aveiro.

2. SEISMICITY OF THE REGION AND THE 11 MAY EARTHQUAKE

The Lorca earthquake of 11 May 2011 occurred in the oriental part of the Betics Cordillera, which is a tectonic zone of common seismic activity in the vicinity of the plate boundary region that separates the Eurasia and Africa plates. The movements of the Africa plate with respect to the Eurasia plate produce a continuous increase of stresses over a series of active faults of northern Africa and southern Spain,

which results in significant seismic activity compared to that of the northern region of central Spain. Lorca is located immediately adjacent to one of these faults, commonly known as the Alhama de Murcia fault, which runs from south-west to north-east for over 80 km through the Murcia province.
The strong motion time series generated by the Lorca earthquake were recorded by several stations of the Spanish Instituto Geografico Nacional (IGN). The M_w = 4.5 foreshock was recorded by stations with epicentral distances between 3 and 40 km. The M_w = 5.1 main shock was recorded by stations with epicentral distances between 3 and 185 km. Figure 1 represents the accelerograms of the main shock, for the North-South (NS), East-West (EW) and vertical directions, recorded at the Lorca station which is located at 2.9 km of the epicentre of the main shock. The earthquake duration is seen to be very short (about 3.0 seconds) and the recorded peak ground acceleration (PGA) is considerably high, namely for the NS component. For comparison purposes, it is referred that the design value of the PGA for Lorca is 0.12g, according to the NCSE 02 Spanish design code (NCSE 02, 2002). Although large, the peak values recorded at the Lorca station are believed to be the result of the very small epicentral distance to that location. To obtain a more comprehensive comparison of the 11 May earthquake with the current seismic design provisions for Lorca, a comparison is made between the acceleration response spectrum of the recorded earthquake and those of the NCSE 02 Spanish design code. Figure 2 presents the 5% damped acceleration spectrum of the main shock and the foreshock NS components recorded at the Lorca station along with the corresponding NCSE 02 design acceleration spectra for the different soil types considered by the code and for a structure of normal importance. As can be observed, the response spectra from the 11 May events exceed those of the NCSE 02 design code for any soil type. For periods up to 0.7 sec, the response spectrum of the main shock exceeds the design ones by factors between 2.4 and 4.0. In the case of the foreshock, for periods up to 0.5 sec, the response spectrum exceeds the design ones by factors between 1.5 and 3.0. As referred, such differences have occurred due to the small epicentral distance of both events to the recording station.

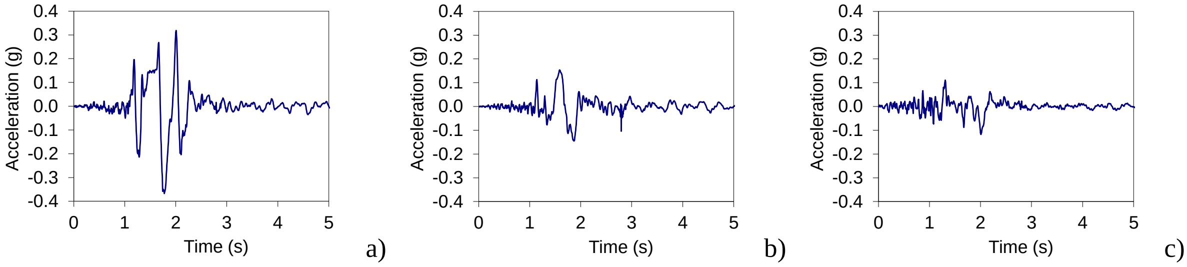


Figure 1. Accelerograms of the main shock recorded at the Lorca station: NS component a), EW component b) and vertical component c) (data from IGN).

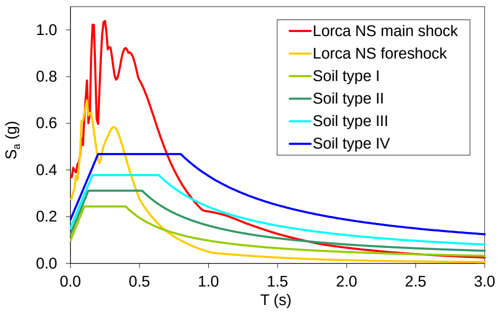


Figure 2. Acceleration response spectra of the NS component of the main shock and foreshock recorded at the Lorca station and NCSR-02 design spectra for different soil types.

3. ANALYSIS OF THE PERFORMANCE OF MASONRY CHURCHES

As part of the diocese of Cartagena, Lorca has a total of thirteen churches, most of them dating back from between the XVth century to the XVIIIth century. However, in the context of this reconnaissance mission, only the seven churches numbered I1 to I7 in Table 1 were visited. These churches are all heritage buildings located in the historical city centre, with the exception of the church of San Diego (I7). It is noted that the church of Santo Domingo (I4) no longer holds religious services and is now a museum. These churches were visited under the guidance of technicians from the Múrcia General Administration of Fine Arts and Cultural Property (Dirección General de Bellas Artes y Bienes Culturales) who also provided inventory records with information about churches I1 to I5, namely details about their construction and state of conservation prior to the earthquake. According to the inventories, these five churches have the same protection level (grade 1) and exhibited a state of conservation graded between average and good, with no reference to any structural damage.

Table 1. Numbering and presentation of the visited churches

I1: Cathedral of San Patricio: XVIth cent.	I2: Church of Santiago: XVth cent.	I3: Chapel of N.ª Sr.ª do Rosário: XVIIIth cent.
	 It was destroyed during the Spanish civil war and reconstructed later	 Side by side with I4 (the left tower is from I4)

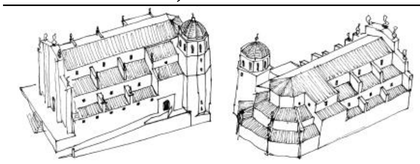
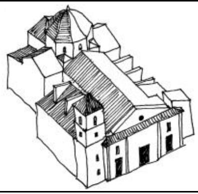
I4: Church of Santo Domingo: XVIth cent.	I5: Church of San Francisco: XVth cent.	I6: Church of N.ª Sr.ª del Carmen: XVIIIth cent.	I7: Church of San Diego: XVIIIth cent.
 A museum side by side with I3	 It is part of a convent		 It is part of a convent

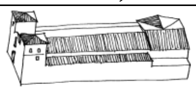
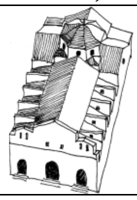
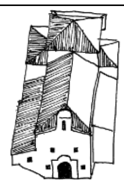
3.1. Architectural characteristics and masonry structure of the churches

For a better interpretation of the behaviour of the churches during the earthquake, Table 2 presents general information about their architectural characteristics, their geometrical shapes and about their masonry construction systems. Some of the data was obtained from the previously referred inventory records, namely the period of their construction, their average height *h* and their urban neighbourhood context. Table 2 also presents general church characteristics that were recorded during the visit, such as the number of naves, levels of buttresses and towers, and the existence of lateral chapels or other architectural features, which are useful to understand their behaviour under seismic loading. The average in-plan dimensions were estimated and correspond to the width *b* of the church façade and to the depth *l* of the church. Although there was no information available for churches I6 and I7, their height was estimated from the height of neighbouring constructions. In addition, it is also referred that the rectangular plans of the churches follow the East-West canonical orientation.

Although all the churches have rectangular plan shapes, some of them, such as the chapel of N.ª S.ª do Rosario (I3) or the church of S. Francisco (I5), exhibit vertical irregularities due to the existence of several roof levels located at different heights which cover different liturgical spaces. Moreover, both the organization and the height of the interior spaces of the churches are such that it gives the idea of a cruciform plan shape despite the fact it is rectangular. It is also noted that the architectural features of some of the churches can play a significant role in their behaviour under earthquakes. For example, churches with lateral chapels have side walls, transversal to the central nave, which separate the chapels and increase the transversal stiffness, while churches with three naves have two longitudinal rows of columns that separate the central nave from the aisles and increase the longitudinal stiffness.

Table 2. Architectural data and masonry construction systems of the churches (n.a. stands for not available due to the inability to have access to that information at the time of the visit)

I1: Cathedral of San Patricio: *b*x*l* = 30x55m^2; *h* > 15m	I2: Church of Santiago: *b*x*l* = 27x45m^2; *h* > 15m	I3: Chapel of N.ª Sr.ª Rosário: *b*x*l* = 15x37 m^2; *h* > 15m
		
Urban position: Separate building Characteristics: Three naves; two levels of buttresses; one tower in the rear; apse Masonry types: Façade wall: M2 Other exterior walls: M2 Buttresses: M5 Tower: M2 Columns and arches: n.a. Vaults: n.a.	Urban position: Separate building Characteristics: Three naves; one level of buttresses; one tower; dome; apse Masonry types: Façade wall: M2 Other exterior walls: M1/M2 Buttresses: M3 Tower: M2/M3 Columns and arches: M4 Vaults: M3 laid flatwise	Urban position: Side by side with I4 Characteristics: One nave with lateral chapels; one bell cell; dome enclosed by lateral walls and topped by a roof; apse and additional constructions Masonry types: Façade wall: M3 Other exterior walls: M3 Buttresses: M3 Columns and arches: M3 Vaults: M3 laid flatwise

I4: Church of Santo Domingo: *b*x*l* = 20x35 m^2; *h* > 15m	I5: Church of San Francisco: *b*x*l* = 20x50 m^2; *h* = 12m	I6: Church of N.ª Sr.ª Carmen: *b*x*l* = 20x45 m^2; *h* > 15m	I7: Church of San Diego: *b*x*l* = 12x32 m^2; *h* ≈ 12m
			
Urban position: Adjacent to other buildings; side by side with I3 Characteristics: One nave with lateral chapels; two bell cells Masonry types: Façade wall: M3 Other exterior walls: M3 Buttresses: M3 Columns and arches: n.a. Vaults: n.a.	Urban position: Located in a street corner Characteristics: It is part of a convent; one nave with lateral chapels; one level of buttresses; one tower; dome enclosed by lateral walls and topped by a roof; apse Masonry types: Façade wall: M2 Other exterior walls: M1 Buttresses: M1 Tower: M1/M2/M4 Columns and arches: M4 Vaults: M3 laid flatwise	Urban position: Adjacent to other buildings Characteristics: One nave with lateral chapels; one level of buttresses; two bell cells; dome; apse Masonry types: Façade wall: M2 Other exterior walls: n.a. Buttresses: n.a. Tower: n.a. Columns and arches: n.a. Vaults: M3 laid flatwise	Urban position: Located in a street corner Characteristics: It is part of a convent; one nave with lateral chapels; one bell cell; dome enclosed by lateral walls and topped by a roof Masonry types: Façade wall: M2/M3 Other exterior walls: M2 Columns and arches: n.a. Vaults: n.a.

With respect to the masonry construction systems found in the Lorca churches that were visited, the following five masonry categories were defined using information obtained from in-situ observations of both damaged and undamaged structural elements:

- Masonry type M1: Small and medium size irregular stones with mortar (Fig. 3a);
- Masonry type M2: Two-leaf wall with an outer leaf made of regular cut stone and an internal leaf made of small and medium size irregular stones with mortar (Fig. 3b);
- Masonry type M3: Brickwork (Fig. 3c);
- Masonry type M4: Regular cut stone (Fig. 3d);
- Masonry type M5: Three-leaf wall with regular cut stone leaves of similar thickness (Fig. 3e).

By referring to these categories, Table 2 also summarizes the masonry construction systems of the visited churches by assigning masonry types to the fundamental structural elements of each church: the façade wall, the remaining exterior walls, the buttresses, the tower of the church, the interior columns, the arches and the vaults.

Figure 3. Masonry type M1 at the church of San Francisco (a), M2 at the cathedral of San Patricio (b), M3 at the chapel of N.ª Sr.ª do Rosário (c), M4 at the church of Santiago (d) and M5 at the cathedral of San Patricio (e).

3.2. Damage observed in the churches

Although the earthquake caused extensive damages to the Lorca churches, the effects were seen to vary significantly from church to church. An overall description of the main damages that were observed in churches I1 to I7 is therefore presented in the following. To facilitate the interpretation of the variety of damages that were found, general categories were defined according to the type of damage and to the structural element where it occurred. Table 3 presents these damage categories which represent the more important damage situations that were found, along with the churches where they occurred. To complement the data presented in Table 3, additional details are also provided with respect to the damages that were observed in some of the churches.

Table 3. General damage categories, mechanisms and churches where they occurred.

Damage category	Church
Partial or total collapse of roofs and vaults of the high altar, of the transept, and of the dome (Fig. 4a and 4b, Figs. 5c, 5d and 5e, Fig. 7a);	I2; I3; I5
Partial collapse of roofs and vaults due to decorative elements that fell (Fig. 6a)	I1; I6
Cracking and detachment of the façade from the remaining walls (Fig. 5a) Cracking and opening of joints in exterior walls of the church and tower (Fig. 8) Cracking between walls and interior structural elements	I1; I2; I3; I4; I5; I6; I7
Cracking at the spine of the vaults (Fig. 4b, Fig. 6b, Fig. 5b)	I2; I3
Detachment of the vaults and arches, of the vaults and walls, and of the vault ribs and panels (Fig. 6b, Fig. 5a, Fig. 7b)	I2; I5; I6; I7
Cracking in buttresses; vertical displacements of the keystones of the arches (in buttresses with arches) (Fig. 4c)	I1; I2
Cracking in the main arches (Fig. 6)	I2; I3; I5; I6; I7
Significantly damaged or collapsed belfry or bell cell; vertical displacements of the keystones of the belfry/bell cell arches (Fig. 7c)	I2; I3; I4; I5; I7


a)

b)

c)

Figure 4. Damages to I2 after the collapse of the chancel and of the transept area, including the dome (a) and (b), and extensive cracking of the buttresses (c).

The most severely damaged church was seen to be I2, due to the collapse of the chancel and of the transept area, including the dome (Figs. 4a and 4b), but other significant damages were also observed such as the extensive cracking of the buttresses (Fig. 4c). The tower of this church was also severely affected due to the occurrence of extensive vertical cracking and loss of confinement of the keystones of the belfry arches. At the time of the visit, an emergency confinement with steel ties along the height of the tower was already in place. Since the construction system of church I1 was seen to be similar to that of I2, the level of damage observed in I1 was surprisingly low. The most relevant damages in I1 resulted of decorative elements of the roof and the façade that fell, namely some of them that fell over the roof of the apse. Other damages include displacements of the keystones of the arches of the first level of buttresses, as well as the detachment of the outer leaf of the exterior walls at some parts.

A surprising situation was also observed with respect to the very different damage levels found in churches I3 and I4, which are side-by-side. While church I3 was severely damaged and exhibited extensive cracking in the walls, arches, vaults and in the dome (Fig. 5), church I4 displayed almost no signs of damage, with the exception of some minor cracking on the back wall. Since the masonry type of these two churches is very similar, and assuming that the founding soils are also comparable, the difference between the damage levels of both churches is assumed to be largely caused by the previously referred vertical irregularity of church I3 which differs from the more regular shape of I4. Although the authors believe the damage differences are mainly due to this factor, other aspects can also influence the damage distribution, e.g. the churches might have different foundation types (an aspect for which there was no available information at the time of the visit).

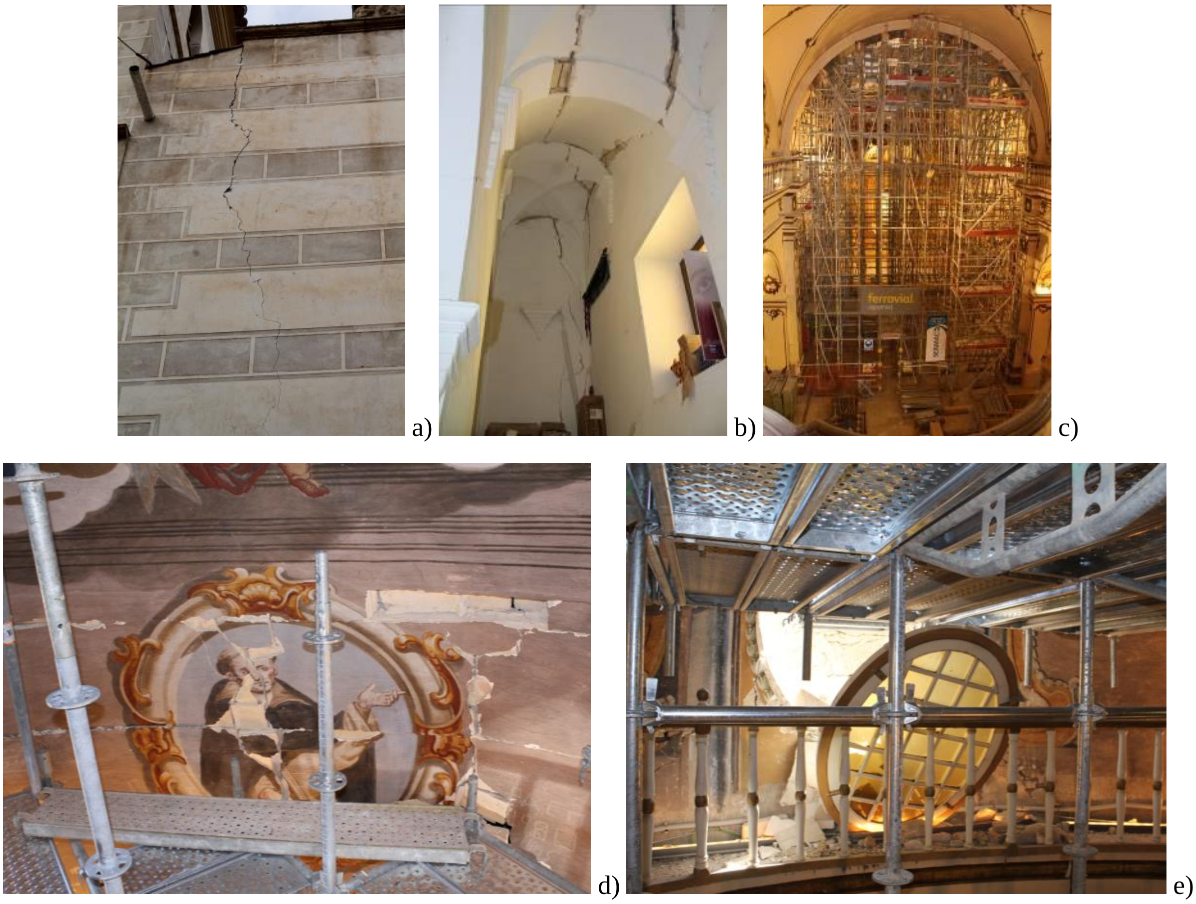


Figure 5. Damages to I3 showing cracking in the façade (a) and in the interior walls and arches (b), emergency shoring of the dome (c), and damages to the dome (d) and (e).

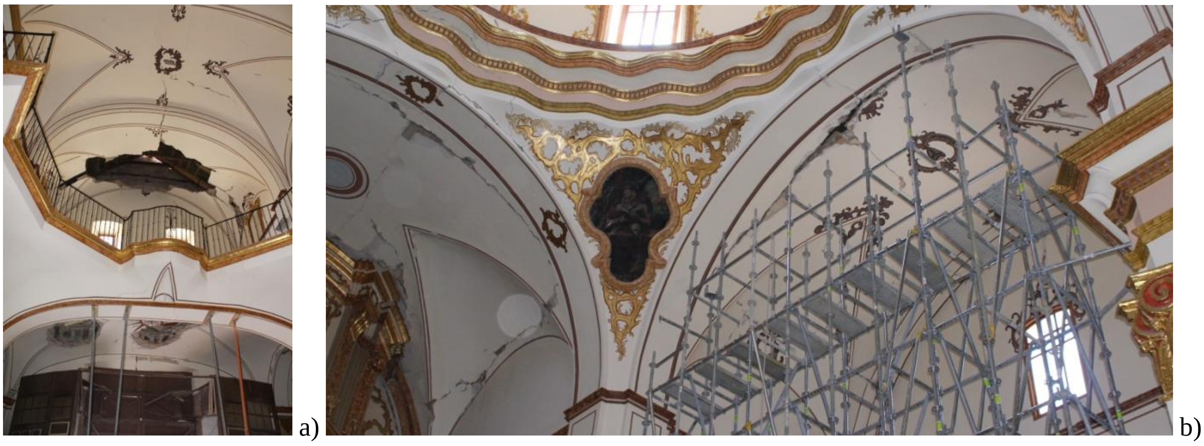


Figure 6. Damages to vaults of I6 from decorative elements that fell (a), detachment of vaults and arches (b).

Church I5 was also extensively damaged, particularly the dome, the vaults and the arches of the transept area which were seen to be in a state of near collapse (Figs. 7a and 7b). At the time of the visit, several temporary shoring structures were in place to avoid further damage and the total collapse of these elements. The tower of I5 also showed significant levels of damage, namely deep vertical cracks in the lateral walls and large vertical displacements of the keystones of the belfry arches (Fig. 7c). At the time of the visit, an emergency confinement with steel ties over the height of the tower was also in place, along with shoring structures for the keystones of the belfry arches.

As can be observed from Table 3, four of the seven churches exhibited severely damaged belfries or bell cells (Díaz *et al*. (2011) refer that other Lorca churches also presented similar damages).

According to Lagomarsino (2012), these components are among the most vulnerable elements of a church and can be significantly damaged even for low intensity earthquakes due to the dynamic amplification of the ground motion as a result of the church characteristics. For example, the bell cell of church I3 was so extensively damaged that authorities decided that it would be best to demolish it.
As referred in Table 2, churches I3, I5 and I7 have domes enclosed by lateral walls and topped by a hipped roof. This architectural feature can also be the source of additional damage to the domes if such walls are damaged by extensive cracking that may lead to their detachment, thus making them vulnerable to out-of-plane failure. Although such situation was not observed in churches I5 and I7, the damage on the walls that surround the dome of church I3 (Fig. 8) was seen to be significant and, at the time of the visit, an emergency confinement of such walls with steel ties was also in place.
Finally, a reference is made to an uncommon damage found in the ruins of the church of Santa Maria (located north of I1). Although no other damages were apparently caused by the earthquake, the keystone of one of the arches (Fig. 9) seems to have been uplifted by the ground shaking.

Figure 7. Damages to the dome (a) and lateral chapels (b) of I5, and vertical displacements of the keystone of one of the belfry arches of the tower (c).

Figure 8. Damage and emergency confinement on the walls that surround the dome of I3.

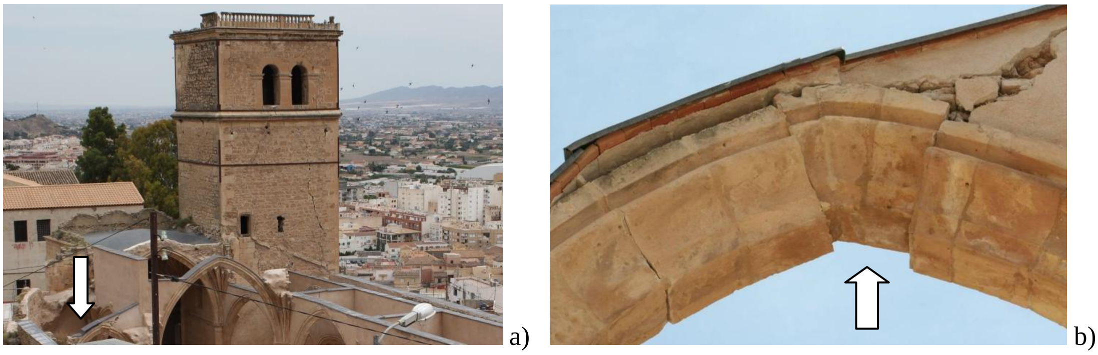


Figure 9. Ruins of the church of Santa Maria (a) and damage detail showing the uplift of the keystone of one of the arches due to the earthquake (b).

4. DAMAGE MECHANISMS

To complement the damage analysis of the churches, damage was classified using the damage index i_d of the Italian church survey form that is based on the identification of collapse mechanisms (GU55, 2006). The form was developed to obtain data to: (a) decide if the building is suitable for immediate occupancy; (b) advise about the need for provisional interventions to prevent further damage due to aftershocks; (c) estimate the restoration costs (Lagomarsino, 2012). The current form considers 28 collapse mechanisms that can occur in different architectonic elements of churches (macroelements) (Lagomarsino and Podestà, 2004). In addition, the high choir mechanism referred by Magalhães *et al.* (2010) was also considered. The list of the 29 mechanisms considered is shown in Table 4. The assessment consists of grading each mechanism that can be activated in a church between 0 (no damage) and 5 (total damage). The score of each mechanism is then combined by a weighted average to obtain a global damage index i_d ranging between 0 (no damage) and 1 (total collapse).

Table 4. Mechanisms considered to assess the damage index i_d.

1.	Overturning of the façade	11.	Shear mechanisms in the transept walls	21.	Roof mechanisms: apse and presbytery
2.	Damage at the top of façade	12.	Vaults of the transept	22.	Overturning of the chapels
3.	Shear mechanism in the façade	13.	Triumphal arches	23.	Shear mechanism in the walls of chapels
4.	Nartex	14.	Dome and drum	24.	Vaults of chapels
5.	Transversal vibration of the nave	15.	Lantern	25.	Interactions next to irregularities
6.	Shear mechanism in the side walls	16.	Overturning of apse	26.	Projections (domed vaults, pinnacles, statues)
7.	Longitudinal response of the colonnade	17.	Shear mechanism in presbytery and apse	27.	Bell tower
8.	Vaults of the nave	18.	Vaults in presbytery and apse	28.	Belfry
9.	Vaults of the aisles	19.	Roof mechanism: side walls of nave and aisles	29.	High choir
10.	Overturning of the transept's end wall	20.	Roof mechanisms: transept		

The analysis of the churches revealed that grading the damage of some of the mechanisms is difficult if it is not possible to go inside the church and if the exterior access to the church surroundings is also limited (e.g. to analyse damage in elevated parts of the church). Hence, it is believed that the grading procedure should be associated to a factor reflecting the level of access to the construction provided to the surveyors during the assessment. A reliability index RI is thus proposed which combines factors reflecting the type of access available to the exterior (Ae_j) and to the interior (Ai_j) of the church. Values of j ranging from 1 to 3 are assigned to Ae_j and Ai_j where 1 indicates that there is no access or that it is very limited, and 2 and 3 indicate that partial and total access is available, respectively. The value of RI is obtained by combining the values of Ae_j and Ai_j: RI < 25% for (Ae_1, Ai_1); 25% < RI < 50% for (Ae_2, Ai_1) and (Ae_1, Ai_2); 50% < RI < 75% for (Ae_2, Ai_2), (Ae_3, Ai_1) and (Ae_1, Ai_3); 75% < RI < 100% for (Ae_2, Ai_3), (Ae_3, Ai_2) and (Ae_3, Ai_3). To illustrate the procedure, Table 5 presents the values of Ai_j, Ae_j and RI assigned for churches I1 to I7 according to the available access (the colour codes reflect the ranges of RI). Given the low value of RI that was obtained for church I7 (which reflects that the available data is insufficient), its damage assessment was not carried out.

Table 5. Factors Ai_j and Ae_j and the reliability index RI involved in the damage assessment of churches I1 to I7.

	I1	I2	I3	I4	I5	I6	I7
Ai_j	1	2	3	2	3	2	1
Ae_j	2	2	2	2	2	1	1
RI	25%-50%	50%-75%	75%-100%	50%-75%	50%-75%	25%-50%	< 25%

The damage grade and the i_d results obtained for churches I1 to I6 are presented in Fig. 10. The values of i_d are coloured according to their value of RI. The results of Fig. 10 indicate that, with the exception of I2, the churches underwent only minor/moderate levels of damage in most mechanisms. Hence, the values of i_d are relatively small. Still, Lagomarsino (2012) indicates that when $i_d > 0.3$, churches are found unfit for use. According to Fig. 10, churches I2, I3 and I5 are also found unfit for use, a scenario which agrees with the decisions made by Spanish authorities. Although its i_d value is only 0.23, church I6 was also considered unfit for use by the Spanish authorities. Given the value of RI for I6, its value of i_d (< 0.3) could be seen as a consequence of its lower RI, thus emphasizing the importance of the information involved in RI and the need to consider such issue in a future review of the procedure.

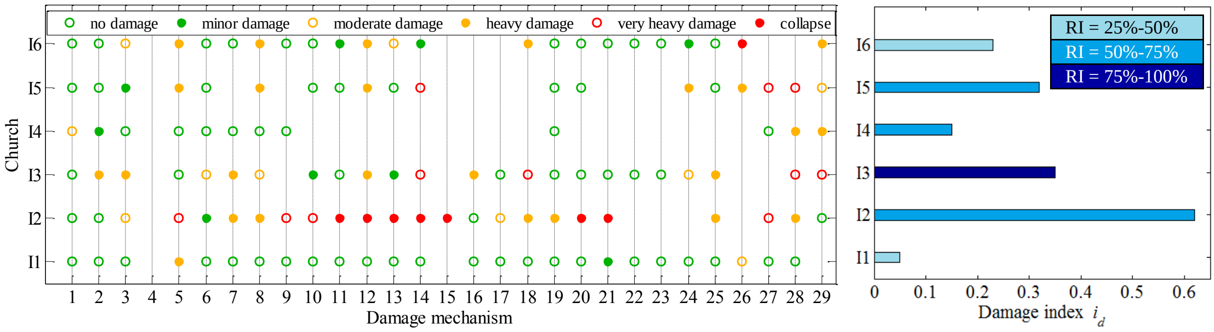


Figure 10. Damage grade of each mechanism and global damage index i_d for churches I1 to I6.

5. FINAL COMMENTS

Heritage buildings such as churches are usually seen to have a high seismic vulnerability as a result of their complex structural arrangements, their geometric proportions, their material composition, and their potentially deteriorated conditions due to their age. Sadly, the earthquake damage found in the churches that were visited during the reconnaissance trip corroborates the truth about such general comment, even for a relatively moderate event such as the Mw = 5.1 Lorca earthquake.

The damage quantification using the Italian approach based on the macroelement concept was seen to be effective to establish if the churches are fit for use immediately after the earthquake. However, the final damage index does not reflect the type of access that surveyors have to the construction when conducting the assessment. To account for this issue, a reliability index RI was proposed. Still, the subjectivity of the mechanisms damage grading for levels between 1 and 4, which depends on the experience of the surveyor, is an aspect that should be considered in a future review of the procedure.

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